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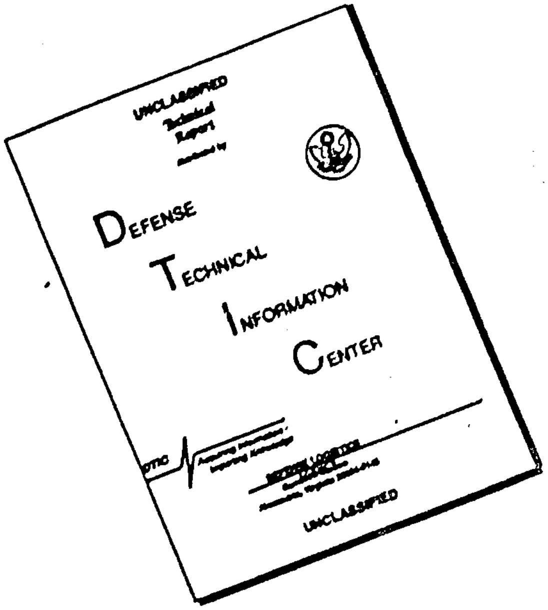

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TEXTILE SERIES REPORT
NO. 116

INFLUENCE OF BLENDING ON PROPERTIES OF WOOL-TYPE FABRICS

QUARTERMASTER RESEARCH & ENGINEERING CENTER
TEXTILE, CLOTHING & FOOTWEAR DIVISION

APRIL 1961 NATICK, MASSACHUSETTS

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INFLUENCE OF BLENDING ON PROPERTIES OF WOOL-TYPE FABRICS

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Project Reference:
7-93-18-020A

April 1961

FOREWORD

This is one of a series of reports in the general field of wool-type fabrics and alternates to conserve wool, with special reference to the physical features by which clothing structures contribute to the protection and effectiveness of the soldier.

This report was prepared under Contract No. DA 19-129-QM-1336, O. I. No. 9075, by Harris Research Laboratories in cooperation with members of the Textile, Clothing and Footwear Division, Quartermaster Research and Engineering Command, U. S. Army, Natick, Massachusetts. It was presented on 17 May 1960 at the Conference on Blend Fabrics, held at Natick under the sponsorship of the Committee on Textile Fabrics of the National Academy of Sciences--National Research Council Advisory Board on Quartermaster Research and Development.

The contract, entitled "Investigation of Properties of Synthetic Fibers in Blends with Wool," was initiated under Project No. 7-93-18-020A; Development of Alternate Fabrics to Conserve Wool, Task: Development of Principles to Improve the Insulating Characteristics and "Comfort" of Textile Fabric Combinations, and was administered under the direction of the Textile, Clothing and Footwear Division, Quartermaster Research and Engineering Command, with Mr. Constantin J. Monego acting as project leader.

This material is Contractor's Report No. 34 in this series, covering the fourth and final quarter of the contract, ending 11 December 1959.

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ABSTRACT

Wool-type fabrics have special combinations of features arising from the chemical properties of wool (high water adsorbing capacity and low flammability) and also special mechanical properties of elasticity and long-range stretch that are in part chemical, based on their polymeric structure. The distinctive structural feature of wool in fabric form is a randomness of arrangement of the individual fibers. This randomness is found particularly in woolens, where extensive fiber rearrangement is produced in fulling, but it is also found in worsteds, which have the most regular arrangement of fibers of any wool fabric. However, blending wool with other fibers, especially in worsted fabrics, usually reduces the randomness of fiber arrangement. This may be desirable for summer clothing but it is not desirable for cold weather use. In woolens, wool-type characteristics can be more completely retained by design to promote fulling.

With respect to the relation of clothing to the physiology of heat balance, the relatively greater thickness and lower density of wool-type structures tend to conserve heat and reduce wicking and the accumulation of moisture. However, the high regain of wool tends to increase the accumulation of moisture and to spread the time required for changes due to moisture passage.

A test system has been developed which shows the immediate and delayed effects of the start of sweating in previously dry clothing. There are interesting clothing possibilities if a wool-type structure can be combined with low moisture adsorption and retention.

INFLUENCE OF BLENDING ON PROPERTIES OF WOOL-TYPE FABRICS

1. The Problem:

The fabric properties considered here are selected ones which are related to the military use of clothing. First, we shall need to look closely at a number of very familiar properties to find the underlying principles. The scientific study of clothing suffers from certain handicaps: we are too familiar with clothing; or working solutions have been found for most of the civilian clothing problems. Moreover, the human body is so adaptable that it can "make do" with a wide range of makeshift answers to clothing problems and can even tolerate the whims of style and fashion or carry the traditional clothing of one climate far into another. However, to gain maximum effectiveness from the large numbers of men in uniform, wearing clothing that is furnished to them and mandatory and that is not the result of free choice or adaptation as in civilian life, we must study the basic principles of clothing in order to get the best large-scale adaptation possible. In this we must keep in mind that the life of the soldier exposed in the field is far more rugged than that of a civilian and that it contains new or increased hazards and requirements.

It may be helpful to consider our problem in terms of the relationship between a 2-dimensional map or drawing of a complex structure, and a 3-dimensional model of the same structure. Properties such as durability, the fit of clothing and its adaptation to body motion, and the protective effects of clothing against fire, rain, and cold or hot environments, can be considered as belonging to a use or physiological dimension of textiles that is related to two other dimensions that are more readily defined and mapped in technical terms. These two technical dimensions are the structural and the chemical properties of textiles. We shall consider these last two dimensions (or perhaps better, two groups of dimensions) first, and shall return later to the third dimension (or group of dimensions) which includes properties in relation to use, or the effects of textiles as clothing, particularly in relation to the problems of heat balance and sweating.

2. Structural and Chemical Properties of Wool-type Fabrics:

a. Fabric and Fiber Characteristics

Before discussing the structural or physical properties of clothing, let us examine the meaning of "wool-type" fabrics. We are all familiar with wool fabrics and, in a general way, with the differences between wool fabrics and fabrics made from other fibers, whether or not we have attempted to really think about these differences and put them in words. Quite a few people in the textile industry have tried their hand at working out the technical conditions controlling the development of wool-type characteristics for either blending or substitution. However, the efforts to obtain fabrics suitable for the special clothing applications in which

wools are principally used, by blending other fibers with wool or by substituting other fibers, have shown that we must have been taking much for granted in making and using wool fabrics. Many effects normal to wool prove difficult to obtain even in blends, and are much more difficult to obtain when wool is completely left out. To arrive at results comparable to those obtained with wool in such a seemingly simple matter as fabric thickness has proved to be a surprisingly difficult problem. Fortunately we are able to learn by blending or by substituting one fiber for another, so that availability of new fibers with new combinations of properties has "fed back" knowledge about the older, more familiar fibers and their structure in fabrics, increasing our understanding of fabric structure for all fibers, whether traditional or new.

In anticipation of evidence that will be presented in more detail as we go along, we may take a summary view of four related structural characteristics of wool-type fabrics: relative thickness, relative hairiness, relative fullness, and a generally random structural arrangement of fibers.

Main Characteristics of "Wool-type" Fabrics

1. Thick and lofty: Low density
2. Hairy: Many fibers outside of the yarns
   Low area of actual contact
   Separation of layers
3. Fulling ability: Fibers can be made to migrate
   Can develop surface cover (wool-plating)
4. Generally random structural arrangement of fibers

Thickness correlates directly with loftiness and inversely with density. This means that a wool-type fabric is relatively lofty, low in density, and high in volume-per-unit-weight as compared with equal weights of other fabrics.

Hairiness of wool fabrics, with many fibers outside the yarns--resulting in a low area of actual contact and a separation of layers--is a property to which less attention has been given than it deserves, possibly because it "comes naturally" and thus is taken for granted. However, in blending with wool, or when wool is replaced by other fibers, even though there is an attempt to keep all the structural characteristics constant, there will very likely be a decrease in hairiness.

The fulling power of wool fabrics of all types is responsible in part for their hairiness, thickness, and relatively low density. This is because, in the wet mechanical action known as fulling or felting, the fibers are made to migrate and to develop a more or less surface cover (wool-plating) accompanied by shrinkage of the fabric. In this fulling, the rather burlap-like assembly of yarns as it comes off the loom is transformed into a cloth that tends to be an

assembly of fibers rather than purely a structure of separate threads: the cover and fullness arise from the fiber structure between and outside the yarns. In worsteds, in which the fibers are relatively regularly arranged in the yarns, the fulling effect desired and obtained is less extensive than it is in woolens. Woolens are "made" in the fulling mill, but even with worsteds the fulling stage of finishing produces a desirable change in the structure of the fabric as it leaves the loom.

In general, the main structural features of wool-type fabrics may be summed up as resulting from a relatively random arrangement of fibers with respect to the direction of the yarn and to the plane of the fabric. Because this randomness of structural arrangement can in principle apply also to fibers other than wool, the chief means of improving the wool-type properties of blends are those which increase the randomness of the non-wool fibers by, for example, adding crimp.

Randomness of arrangement of structure is different from the randomness of fiber distribution along yarns and across cross sections that is of concern in discussions of evenness of blending. The randomness of structure involved in wool-type fabrics refers to the direction in which the fibers or elements of fiber length are oriented. However, more random fiber distribution in the sense of even blending may also contribute to randomness of direction or orientation, if one or more of the kinds of fibers which are being blended differ in the tendency toward randomness of direction, as is usually the case.*

An illustration of one aspect of randomness of structure is shown in a study of the relative hairiness of three serge fabrics (1). Surface profiles were taken by folding each fabric at 45 degrees to the warp and filling. The most hairy surface was found to be that of an all-wool serge; intermediate in hairiness was the surface of a fabric with 50 percent wool/50 percent acrylic fiber; the least hairy was the surface of a 100 percent acrylic serge. We shall return to other methods of measuring hairiness and other examples of the significance of this type of randomness as we proceed.

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* In this presentation, we usually use data obtained from fabrics, considering the combined effects of randomness of fiber arrangement both within and outside of yarns. M. J. Coplan, in the first paper of this conference, and in the series, "A Study of Blended Woolen Structures," Parts I through V and continuing, in the Textile Research Journal, has demonstrated differences between wool and other fibers in detailed arrangement within the yarns. These differences include lower density of packing for yarns containing wool and are related to the randomness of structure discussed here.

While we have noted that hairiness and other special features of wool-type fabrics arise from the relative randomness of fiber arrangement, we should add here that some special features of wool fabrics are not structural alone but are specific to the wool fiber and its chemistry. The following tabulation lists a number of chemical as well as structural fiber properties in which the range of values characteristic of wool is different from the range normal to other fibers unless special means have been taken to achieve a range similar to wool. Indeed, any of the purely structural features of wool fibers can be duplicated in other fibers; thus, many man-made fibers are now available with more or less permanent crimp and in varying diameters and lengths. In wool yarns, of course, one always gets an assorted range of fiber diameters and lengths. R. M. Hoffman (2) was one of the first to recognize the value of varying fiber sizes in reducing the closeness of packing and increasing the loftiness of fabrics produced from man-made fibers.

<u>Fiber Characteristics Which Can Be "Wool-Type"</u>

Crimp	Felting	Long-range elasticity
Varying length	Regain	Crimp resistance to small strain
Varying diameter	Burning Characteristics	Yielding to large strain

Some of the properties tabulated above have not, at least not yet, been made available in man-made fibers. <u>Felting</u> appears to be a unique property of wool and of a few other animal fibers. From analysis of what happens when changes are made in wool fibers (3), felting appears to depend on a combination of several properties, among which the most important are directional friction difference as well as long-range stretch and recovery (elasticity) of the wool fiber. While it has appeared to many students of wool that one physical characteristic (the overlapping scale structure of the fiber surface) could by "ratchet action" account for the directional friction difference, it is by no means certain that this is the whole story, for some have postulated that frictional difference is based on the molecular arrangement or chemical structure of the fiber.

In contrast to felting, <u>crimp</u>, <u>range of diameter</u>, and <u>range of length</u> are purely structural properties that have been provided in man-made fibers, often in types especially recommended for blending with wool. However, in addition to felting, certain other properties are relatively special to wool, and are related in varying degrees to the chemical nature of the fiber. These chemically-based physical properties include <u>long-range elasticity</u>, and <u>crimp resistance to small strain</u> with <u>yielding to large strain</u> (6, 7). The <u>regain</u>, or water adsorbed within the fiber substance, is a "chemical" characteristic that is higher for wool than for any other fibers except the regenerated cellulose rayons, which are similar to wool in water content. This "regain" property will be considered further in connection with the

influence of clothing on the heat balance of the body. The burning characteristics of wool in fabric form are typically a low flammability and a relatively high resistance to burning, with a desirable char structure and no melting. This "chemical" property has in the past been of greater importance to the military than to civilians, but it can certainly be of importance to everyone.

The elastic properties of wool fibers, although pointed out as part of the "wool-type" picture, will not be discussed at this time since they have been the subject of extensive study by many workers, including Dr. Walter Hamburger, M. J. Coplan, and their associates, in a series of papers on the "Mechanics of Elastic Performance of Textile Materials" (4, 5). The factor of initial crispness with yield to larger strains, which has been particularly developed under the concept of "compliance ratio" by Hoffman (6) and Hoffman and Beste (7), is uniquely developed in certain natural and man-made protein fibers, of which wool is the classic natural-fiber example. This would be of importance in discussions of fit and adaptation to action in clothing, but it cannot be taken up further in the present discussion.

b. Surface Characteristics:

In a systematic study of knit underwear fabrics, Hock, Sookne, and Harris have illustrated the influence of blending on surface characteristics (8). The hairiness and low area of actual contact characteristic of wool are demonstrated by the print made on water-sensitive paper by swatches of moist fabrics. The swatch of 100 percent cotton makes the darkest print, showing the greatest contact. Less contact is shown for 25 percent wool/75 percent cotton, and still less for 50 percent wool/50 percent cotton. In the series studied, the major effect of contact was accomplished at the 50/50 level, with relatively little further change at higher wool content.

The contact effect was measured in several ways, including subjective impressions of chill when swatches of moist underwear were applied to the skin, and objective measures of changes in temperature when the moist fabric was applied to a surface which was initially in heat-flow balance at 37.5°C. As shown in Figure 1 (on page 6), the temperature of the surface first drops, due to increased heat flow to the moist fabric, then returns to a new steady state at a lower temperature than that without the fabric. In general, there is less initial chill and a higher steady-state temperature with the higher percentage of wool content. This is interpreted as an example of how differences in extent of contact result in corresponding differences in the rate of heat flow from a warm surface to the underwear.

It should be pointed out that there are many arbitrary features in a laboratory study such as this. Although the results depend on the level of moisture content, similar temperature sequences after contact (though through

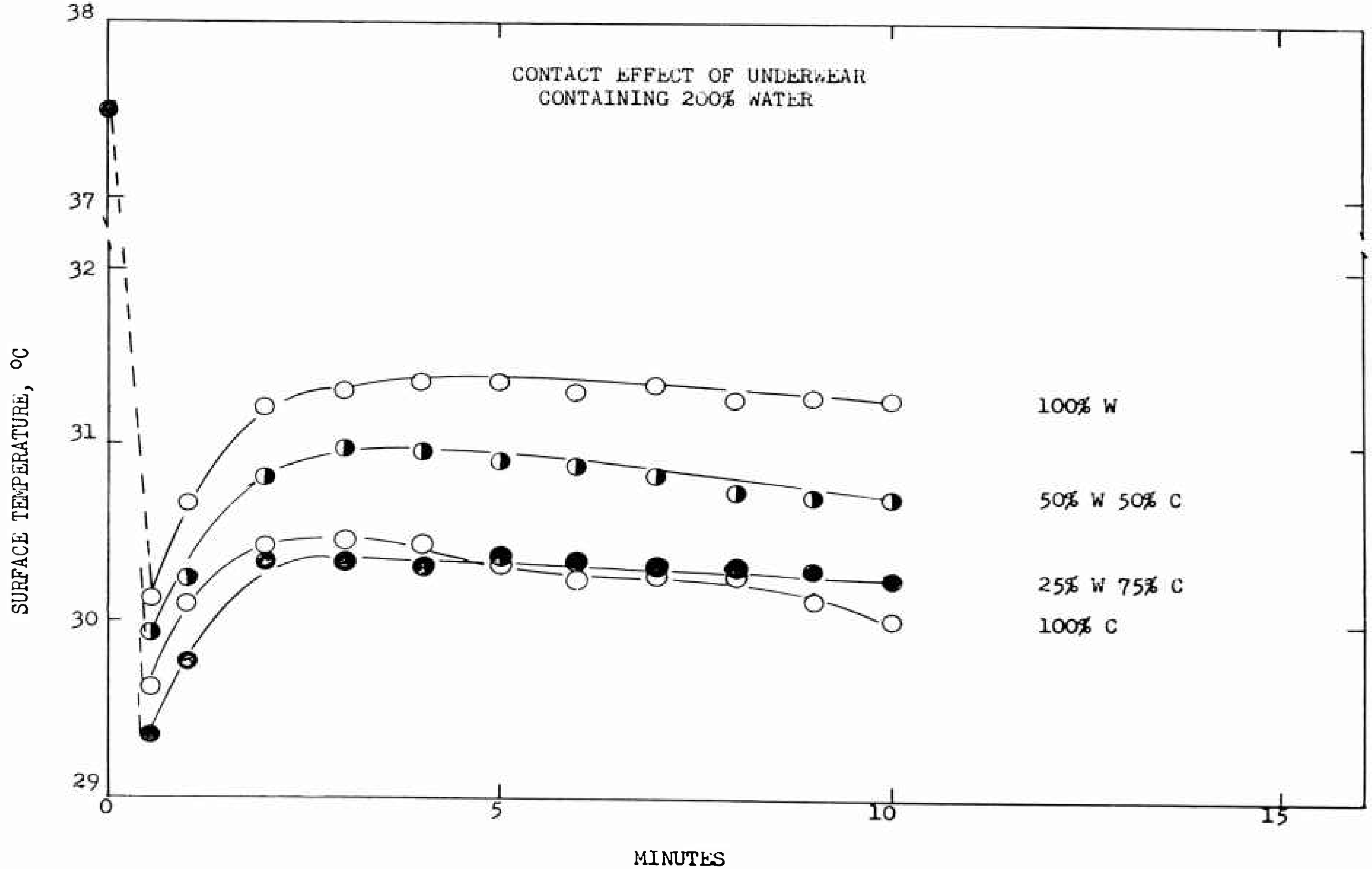

Figure 1. Change of temperature of a surface originally at 37.5°C., on contact with wet underwear fabric with indicated percentage of wool (W) or cotton (C). From Hock, Sookne, and Harris (1944).

a smaller temperature range) were observed with dry fabrics by Rees in 1941 (9). Also, by reducing the heat capacity of the heat source and by insulating it well so that the main route of heat loss would be through the surface fibers of a fabric, Hollies, Bogaty, Hintermaier, and Harris were able to show the effects of number, length, and kind of surface fibers (10). These tests are familiarly known within the laboratory as "hot-penny" tests, from the size of the insulated piece of metal. (Lest any British friend misunderstand, "hot farthing" would be more precise, because the piece of copper was quite a bit smaller than even an American cent.) The heat-transfer-through-surface-fiber effects obtained by the "hot-penny" tests were verified by means of models made with coarse monofils. Similar relationships to number and length of fibers per unit area of surface can be worked out for conventional fabrics by thickness and pressure relationships (11) or by counting the number of fibers and their length from fabric-edge profiles. A simple, overall relationship that increases with the increasing effectiveness of a hairy surface as an insulator is given by the half-time for cooling in "hot-penny" tests. The half-time for cooling is the time required for the small copper disc, well insulated except for one surface that is in contact with the fabric (or, rather, with the surface fibers of the test fabric), to cool half-way from its initial temperature to room temperature. Like the half-life of radioactive materials, the half-time for cooling varies inversely with the rate of change, in this case with the rate of heat transfer through the surface fibers.

Table I shows results of the "hot-penny" test as applied to some known textile structures and to some blends (10). The shearing of an all-wool serge, which is known to shorten the surface fibers (this has been verified by edge profiles), also shortens the cooling time, i.e., increases the cooling rate. A blended serge with only 50 percent wool, and a 100 percent nylon fabric of similar construction, both show shorter half-times, i.e., faster rates of cooling through their surface fibers, than the all-wool. Going further, differences are shown between two twill lining fabrics, one a spun staple viscose, the other a filament viscose, in the direction of even more rapid heat transfer for the filament fabric, corresponding to the relative "cool feel" of the filament fabric on contact with the skin. A classic example of this difference of contact sensation of warmth is the cool feel of linen compared with cotton or other short-staple fabrics: the cool feel of linen can be attributed to the smoothness or low hairiness of its surface.

TABLE I

RATE OF COOLING OF SEVERAL TYPES OF FABRIC SURFACE

FABRIC	HALF-TIME FOR COOLING* (seconds)
All-wool serge	78
All-wool serge, sheared	68
Blend serge, 50% wool	63
All-nylon serge	41
Spun staple viscose twill lining	37
Filament viscose twill lining	31

* Time required to cool halfway from initial temperature to room temperature

Data from Hollies, Bogaty, Hintermaier, and Harris, 1953 (10).

The changes of surface hairiness in blending are shown further in Table II, which shows three series of serge fabrics (12), each series with increasing amounts of acrylic or modified acrylic fiber. There is relatively little change or increase between the cooling times of the 70 and 85 percent wool blends, but at the 50 percent level a decrease in cooling time is evident and with zero percent wool the cooling time is much shorter, indicating a marked difference of surface structure.

TABLE II

EFFECT OF HAIRINESS, AS SHOWN BY HALF-TIME FOR COOLING, FROM BLENDING ACRYLIC FIBERS A, B, OR C WITH WOOL IN A SERGE FABRIC

WOOL CONTENT (%)	HALF-TIME FOR COOLING* BLEND A (sec)	BLEND B (sec)	BLEND C (sec)
100	71	68	73
85	74	71	72
70	76	65	70
50	71	58	69
0	53	49	49

* Time required to cool halfway from initial temperature to room temperature

Data from Bogaty, Hollies, Hintermaier, and Harris, 1953 (12).

c. Internal Structure Characteristics:

The basic randomness of fiber arrangement that is characteristic of wool-type fabrics is evidenced by their internal structure as well as by their surface hairiness. Thus the time required for water to rise 1 inch in a vertical wick is longer (wicking is less free) with increased wool content or with physical treatments which increase the randomness of the fibers within the yarns (12, 13).

Another property related to internal structure is thermal conductivity through the complete fabric. Speakman and Chamberlain in 1930 (14) showed small but definite differences in the thermal conductivity of different fibers both in the form of packed assemblies of loose fibers and in fabric form. Thermal conductivity depends mainly upon thickness but, if put on a unit-thickness basis, it depends secondarily on the kind of fibers and their physical arrangement. Bogaty, Hollies, and Harris (15) have interpreted thermal conductance in terms of fiber arrangement resolved into components perpendicular to or parallel to the fabric surface. They have found that wool-type fabrics differ from other fabrics in their fiber arrangement and in their thermal conductivity.

This difference is seen in the relation of thermal conductivity to pressure, as shown in Figure 2 (on page 10), in which the thermal conductivity of various fabrics, in terms of an equivalent thickness of air, is plotted when the fabric is compressed between two plates at a range of pressures. One can refer to the original paper for a detailed interpretation of the results in terms of fiber arrangement. For the purpose of this presentation, the relative constancy of conductivity of wool fabrics, and the increase in conductivity of other fabrics (non-wool) with increased pressure, points to a considerable difference in structure, a difference which is mainly that of greater randomness of fiber arrangement in the wool fabrics.

d. Retention of Wool-type Characteristics in Blends:

Worsted fabrics: The thickness of fabrics at fairly low pressures is a result of a combination of both surface and internal structure properties. One of the main conclusions drawn from the earlier systematic trials of blended serges (1, 12) is that in wool-type fabrics, density of fiber substance has little influence on yarn density, effective yarn diameter, or fabric thickness. When one uses finer nylon or acrylic yarns in an attempt to compensate for the lower density of fiber substance (about 1.15 grams/ cm^3 compared with 1.30 for wool), one produces very much thinner and leaner yarns and thinner and lighter fabrics. Increasing the texture (yarns per inch) brings the weight of the fabric up somewhat but has little effect on fabric thickness, which is determined primarily by the thickness of the yarns. The fact is that the thickness and the density of wool-type fabrics are determined by the compactness or randomness of the fiber arrangement and by the hairiness of the yarns rather than by the cross-sectional

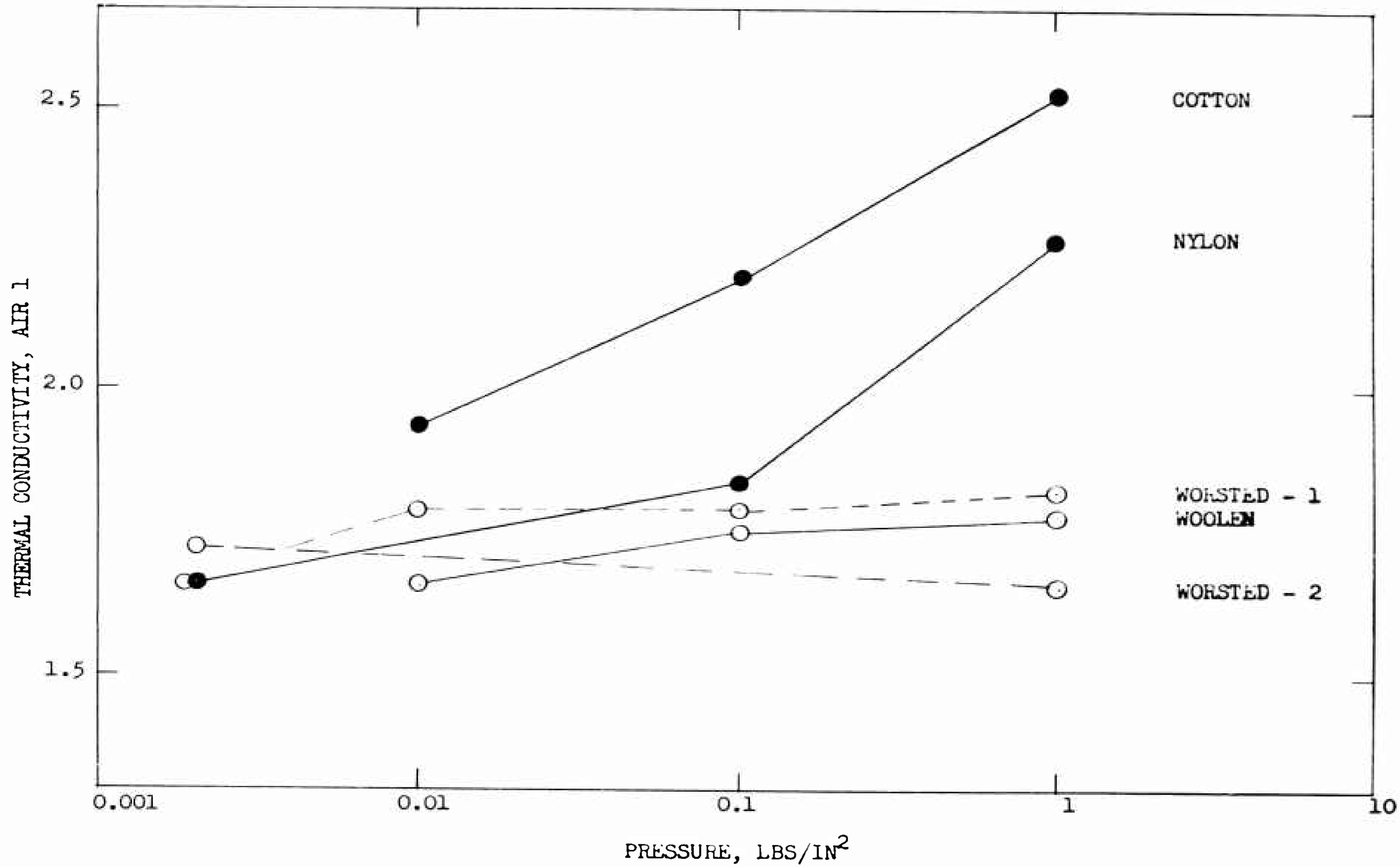

Figure 2. Change of thermal conductivity (relative to air) with pressure (thickness) for fiber arrangement in fabrics of different fibers. From Bogaty, Hollies, and Harris (1957).

area of the fibers themselves. Thus the deliberate use of finer yarns made of fibers which lack the permanent three-dimensional crimp of wool was, it was learned from the results, equivalent to taking not one but two steps toward thinner fabrics. We can at least say, as so frequently one must in the laboratory, "Well, now we know what not to do!" On the positive side, we know that yarn size in wool-type yarns depends on fiber crimp and on hairiness more than on fiber density or on the sum total of fiber diameters in a cross section. It is, however, affected by individual fiber diameter or size, so that higher denier man-made fibers result in increased hairiness, effective yarn diameter, and fabric thickness.

In a more recent series of blended serge fabrics, prepared as a joint Quartermaster—Air Force study (16, 17), the yarn sizes, textures, and weights were more nearly the same in the all-wool controls and in the various blends. Figure 3 (on page 12) shows the relation between thickness and weight for six pairs of wool blends with 15 and 30 percent of non-wool fiber of different types. One can see, from the thickness of the all-wool control (marked W) that four of the 15 percent blends have a thickness that is equal to or greater than that of the wool control. However, in all cases the 30 percent blend is less thick than the wool control.

The tendency to produce thinner, less hairy fabrics by blending wool with man-made fibers can be an advantage when thin fabrics are desired, as for summer wear. Blending with high-strength fibers helps in the spinning of finer yarns, and the relatively slight effect of moisture on the mechanical properties of low-regain man-made fibers is an aid to appearance. The presence of a substantial percentage of wool helps to achieve to a recognizable degree those wool-type characteristics that are based on a relatively random fiber arrangement, even though these summer fabrics may be made on worsted or cotton-type systems which emphasize regularity of fiber arrangement. An extensive study of such fabrics for Army summer uniforms (18) has brought out the advantages of certain blends for worsted-type fabrics for summer wear.

The conclusions reached in studies on the influence of fiber blending on worsted fabrics (1, 10 to 13, 15 to 18) can nearly all be expressed in terms of either the relative regularity or the randomness of the fiber arrangement in the yarns and in the fabric structures. These conclusions can be listed as a series of points to which the designer can give attention. In the choice of fibers, these points for design may be reduced to improving the wool-type characteristics by such means as using relatively coarse deniers,

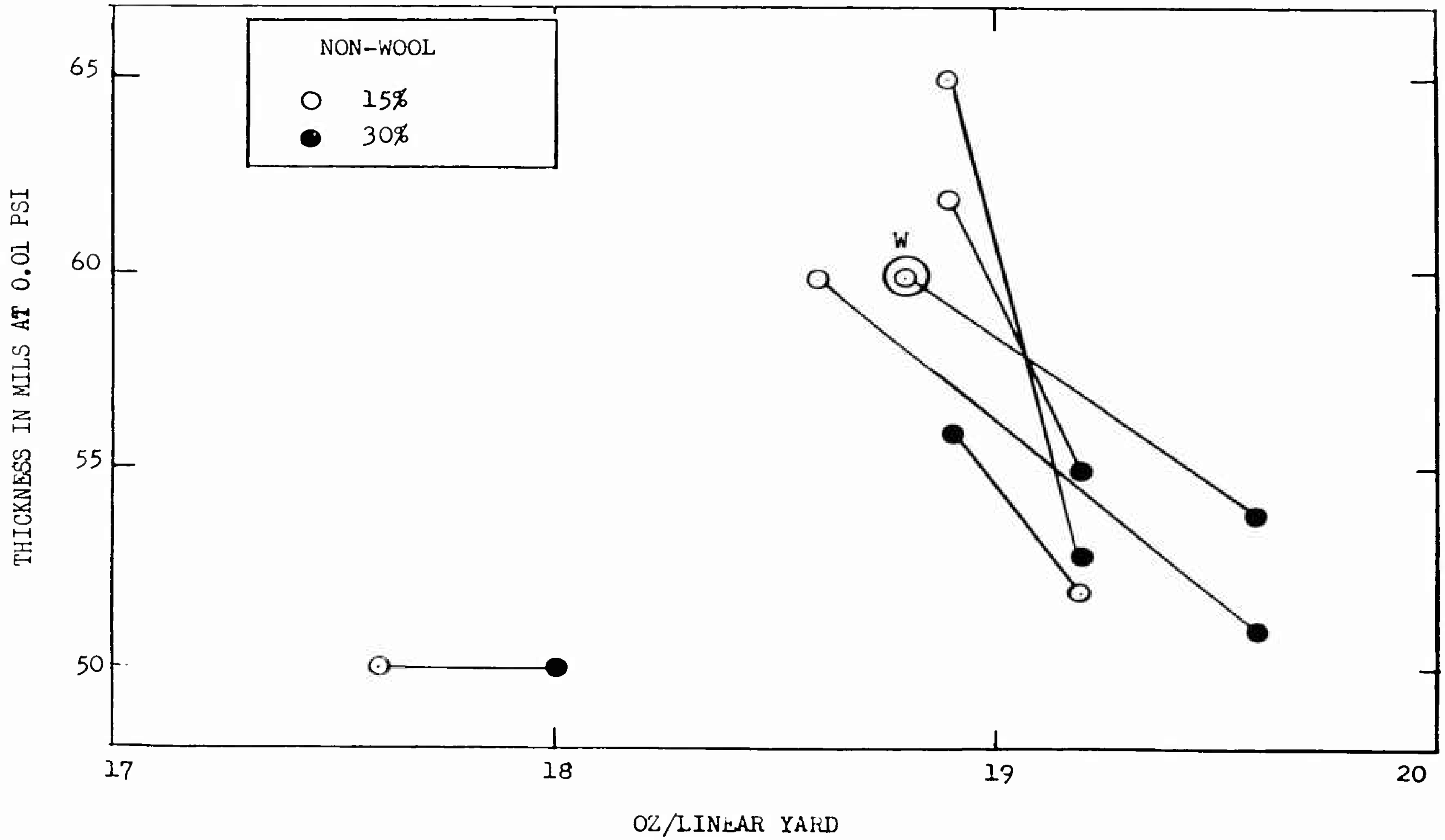

Figure 3. Relative thickness and weight of six blended serges (with 15 and 30 percent non-wool content) and the all-wool control (identified by large circle marked "W" which coincides with one of the 15 percent blends). From Monego (1959) and Menkart (1959).

a range of deniers, permanent crimp, and varying short lengths.* In addition, there is the possibility of obtaining greater fabric thickness by selecting the proper yarn twist, twist direction, yarn size, and texture, provided that the corresponding variations in fabric appearance will be acceptable. A longer float length in weaving, and also certain patterns, will promote fulling and the flexibility of the finished cloth.

Woolen fabrics: Woolen fabrics are usually thicker than worsteds. Many Navy fabrics, and the Army 16-ounce shirting fabric, are woolens, not worsteds. At present, the Army 16-ounce shirting is produced as an 85/15 wool/nylon blend (19), with the nylon serving chiefly to facilitate the spinning and to increase the strength and durability. The first of a series of experiments (1) to conserve wool by using a high proportion of non-wool in the 16-ounce shirting showed that a key factor for blended woolens is the promotion of fulling, and that this is greatly aided by a low twist in the yarns, by a weave design with increased float length, and by an open texture in the loom.

In the woolen shirting fabrics, it is desirable to retain to the maximum the wool-type characteristics of thickness and random fiber arrangement. Fortunately, this can be done to a very large degree by the more extensive felting or fulling action in the finishing of woolen fabrics. Not only is thickness retained but also, because the wool fibers migrate and form a surface cover, a "wool-plating" or a practically pure wool surface is obtained. If the fabrics are fulled to approximately 25 percent shrinkage in length as well as width, adequate cover and thickness can be obtained without napping. If possible, it is desirable to avoid napping to conserve strength and avoid carrying the non-wool fibers onto the surface. By combining the principles which are useful in preserving randomness and in obtaining thickness in worsteds with the extensive fulling possible in woolens, it is possible to be relatively independent of the type of blending fiber used, up to a 35 percent non-wool content, in the 16-ounce shirting fabric (20). A tentative specification has been drafted for a 16-ounce shirting--with 65 percent wool, 20 percent rayon, and 15 percent nylon--which has proven itself practical in mill production trials and wear tests. Its durability in wear trials is only slightly lower than the durability of the 85/15 wool/nylon shirting; the durability seems closer to an older type of all-wool 16-ounce shirting that was replaced by the more durable wool/nylon blend.

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* Certain man-made fibers, particularly polyamide and polyester fibers, can contribute to strength when used in sufficient percentage, but in many uses extra strength is not needed, provided that the yarns can be spun and woven. Hence an important function of these high-strength fibers can be to permit the spinning and weaving of finer yarns, and the weaving of lighter fabrics for summer use, than can be made at a given cost from wool and mohair alone. Some of the potential gain in strength can be relinquished in favor of other gains in "hand," surface character, or other wool-type characteristics.

While extensive fulling can retain the wool-type properties of woolen fabrics designed for maximum fulling, to go much further than 35 percent in non-wool content is likely to produce changes in the direction of leanness, thinness, and lack of cover; that is, it becomes a yarn-structured fabric rather than a fulled fabric. A higher percentage of non-wool content causes different fibers to vary noticeably in their effect on the fulling power of wool (21) and there are patent claims (22) that certain acrylic fibers prevent felting. Hence, while certain fabrics containing wool can be made more washable by blending to decrease felting, they are likely to be changed to a fabric structure which is less "wool-type."

3. Physiological Properties of Wool-type Clothing:

One of the "third dimensional" (the use or physiological) features of wool-type fabrics that has been of continuing concern to the Quartermaster Corps has been their use in clothing to protect against cold. This concern is reflected in attention given to the thermal conductance, thickness, and surface contact of wool-type fabrics. However, to deal with the use of clothing in protecting the body we must go beyond the insulation of a dry fabric, since the influence of moisture is also important.

The moisture problem in clothing for a cold climate arises not only from rain or snow from the outside but also from perspiration from the inside. Some water vapor is always leaving the skin as insensible perspiration, but where the body is tending to overheat, there is active sweating inside the clothing. Overheating and sweating create very severe problems in cold weather clothing, since clothing that is inadequate for light or stationary duty in a cold climate can be much too heavy for more severe work. It is easy to recall how cold one gets, even in an overcoat, when standing on the corner waiting for the bus, and how hot one gets when having to walk all the way home through the deep snow that stalled the bus.

The range of total energy expenditures or range of work levels (in the sense of total body effort or metabolism, not of external work) is shown in Table III (23). Thus, sitting in a lecture hall, a man expends about 100 watts of energy, or 1/7 unit of horsepower, even though he may be doing no useful external work or, in another sense, no useful work. At the other extreme, when a man is physically working to the limit of his capacity, he expends over 746 watts of energy, or one unit of horsepower, but much less than this will be converted into external work, such as weight times height in climbing a grade or shovelling snow or earth. The excess of the energy expended over the energy converted into external work is lost from the body as direct heat or as sweat, so we can be sure that a man working at the rate of one horsepower is also "sweating like a horse."

TABLE III

APPROXIMATE ENERGY RATES FOR A MAN

Work level	Watts	Horse-power
Sitting	100	0.13
Light to moderate effort	190-370	0.25-0.50
Exhausting effort	746	1.00

Data from Forbes, 1949, in Newburgh, "Physiology of Heat Regulation" (23).

There are two main ways that heat is lost from the body. One is direct heat loss by conduction, convection, and radiation. Direct heat loss depends upon temperature differences. The second method is heat loss by evaporation, which depends on differences in vapor pressure and not directly upon differences in temperature. In fact, heat can be lost to atmospheres warmer than body temperature by evaporation, which is what keeps us alive when the thermometer hits or goes above 100°F. Generally, in the cold, in clothing which is causing a man to sweat, the difference in vapor pressure is in the same direction as the difference in temperature, with the highest level at the surface of the skin and the lowest level outside the clothing. In heavy cold-weather clothing, the two methods of heat loss are not separate and parallel but are combined, with more of the energy transfer at the skin level being by evaporation, while more of the same flow of energy at the outer level of the clothing is by direct heat loss. Accompanying this change of mechanisms is an accumulation of condensed water in the clothing.

We know from several lines of evidence that heat transfer in heavy clothing is by means of a combined and changing flow of energy. One piece of evidence is the water which accumulates in the clothing. After 2 hours of hard work in the cold, the underwear and outer layers of clothing can contain water amounting to from 40 to 70 percent of the ordinary weight of the clothing, according to tests made by Belding (24) for the Office of The Quartermaster General.

The question has been asked as to whether the water in the clothing got there by evaporation from the skin with condensation, in which case it would help in the energy loss process; or if it got there by wicking or blotting from the skin, in which case it would be far less effective in energy transfer.

Tests by Hollies (25) have shown that in wool-type fabrics there is a minimum of blotting or wicking, and that water transfer is largely by evaporation with condensation in the cooler parts of the clothing. Moreover, Hollies also showed that, at the levels of water content reached in clothing, there is very little sidewise wicking in the plane of the fabric itself. If the fiber has high regain, as wool has, a large part of the water held in the fabric may not be liquid water at all but a form of water that has been adsorbed within the fiber substance. Most of the remaining water is immobilized in the fabric, either in isolated capillaries produced by local contact of fiber with fiber, or held as individual droplets along the free lengths of fibers, like drops of dew on a spider web.

There are probably differences with respect to the distribution and capillary mobility of water within the fabric, depending on the nature of the fibers in the blend. Thus Minor, Schwartz, Wulkow, and Buckles (26), in studies of the behavior of liquids on single fibers, have shown that, just as a long cylinder of unsupported liquid breaks up into drops, so will a thick film applied to a fiber. However, on crenulated or grooved fibers, such as the usual viscose rayon, a liquid will wick along an individual fiber, whereas on wool fibers, a liquid will stay in drops without spreading.

Although we need to know more about the distribution of water in clothing in use, we have in the meantime been learning about the effects of heat and moisture flow. A test system has been developed at the Harris Research Laboratories to measure how much energy can flow by the combined mechanisms of heat and moisture in a given clothing assembly. Figure 4 (on page 17) shows the results of such a test. The test system differs from human reactions in that it is unwilling to tolerate either chilling or overheating and automatically draws just that amount of power required to keep it at a constant temperature. In these tests, a temperature gradient between the "skin" of the test cell at 30°C. and the cold environment at -3°C. is first set up through dry clothing. The corresponding level of power consumption is measured, this being the power supply which maintains this steady state under dry conditions. Sweating is then allowed to begin by quickly removing an impermeable plastic film, which had been placed between the skin and the clothing, without disturbing the clothing. Underneath this plastic film there is a layer of chamois leather containing enough water so that it will neither dry out during the sweating period nor drip. To make sure that all the water transfer from the wet "skin" to the clothing is by evaporation, a layer of vapor-permeable but water-impermeable plain cellophane covers the chamois under the plastic film and is left in place throughout the tests. When sweating begins, two things happen: the power required to maintain the skin at constant temperature increases and the temperature of the clothing also rises. The power stays constant at a new, higher level all the time that sweating is going on, as far as we have

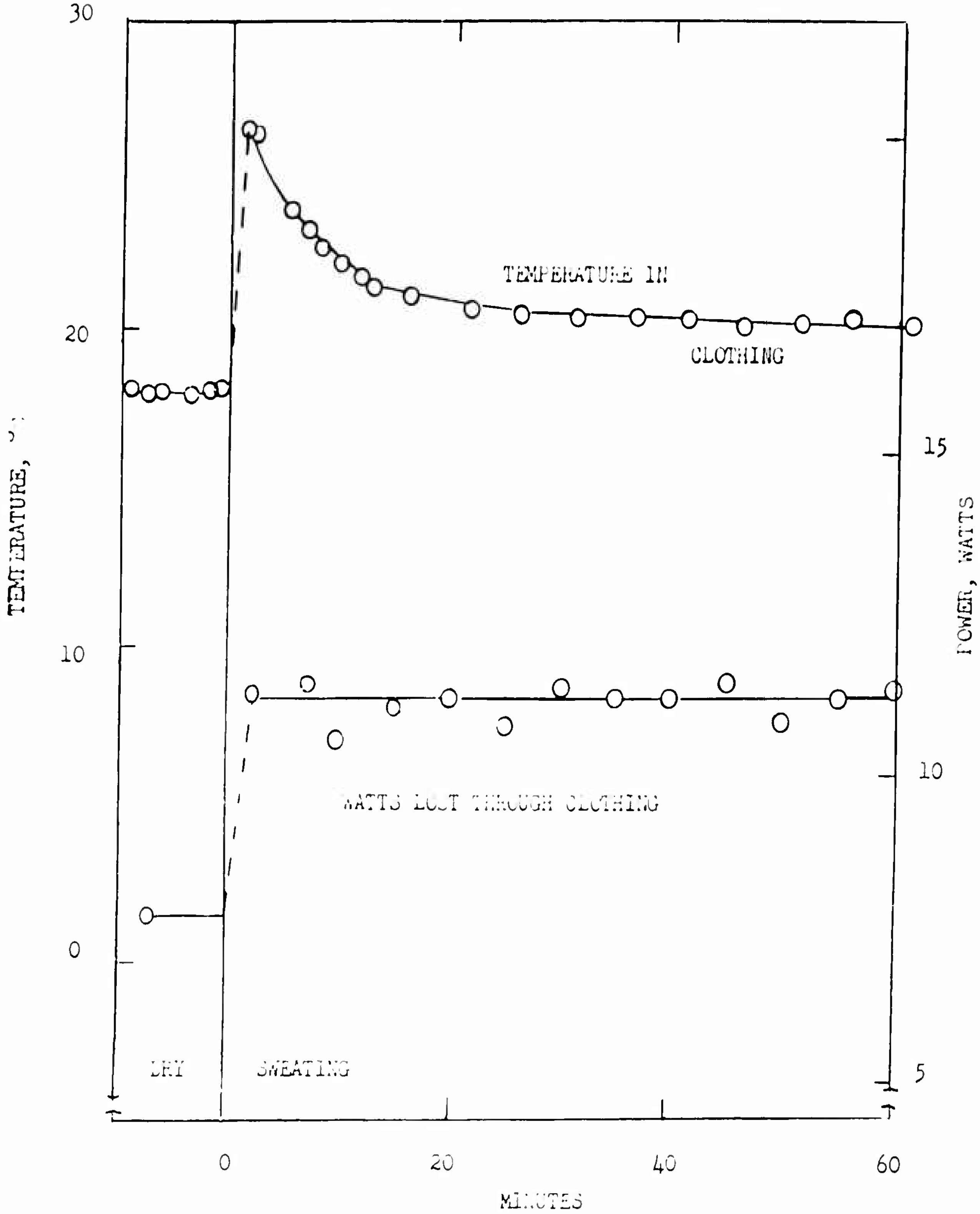

Figure 4. Temperature in clothing and watts of energy lost through clothing before and after starting sweating in a laboratory system that maintains a constant skin temperature (30°C) and air temperature (-3°C).

followed it. The temperature of the clothing then falls, but to a new level which is higher than before. At the same time, water is accumulating in the clothing. This sequence of events is additional evidence that water transfer in clothing in a cold climate is primarily by evaporation and condensation and not by wicking. It also shows that while sweating is going on, the combined rate of energy flow is independent of water content of the clothing over a large range of water content.

The effect of sweating on the temperature of the clothing differs with various fibers. Figure 5 (on page 19) shows the test results where two layers of wool serge totalling 0.5 cm in thickness were used (the temperature data of Figure 4 repeated), 8 layers of wool totalling 2.1 cm, and a 2.5 cm polyester fiber batt which, while thicker, has a much lower regain than the wool. The sequence of temperatures for the thick polyester batt has the same general appearance as that for the thin wool covering, although the range of temperature change is smaller. With the larger amounts of wool, the sequence differs in being more spread out in time, which is probably due in part to the larger amount of fiber with high regain, that is, high capacity to adsorb water. However, the density of the wool fabric is greater than that of the fiber batt and exact relationships between regain, density, and amount of fiber surface have not yet been worked out, so there may well be future improvement of our understanding of these effects.

The results shown in Figure 5 indicate that there is a heat-of-condensation effect even with fibers of very low regain but that this effect is greater with fibers of high regain. Cassie and Baxter (27) have suggested that this heat-of-condensation or heat-of-regain effect is a desirable stabilizing influence, which may be true in certain types of clothing use but not in others. Viewing clothing as part of an automatic control system, it may be undesirable to increase the lag between the call for cooling by sweating and its accomplishment. This would be particularly important in light clothing for warm conditions. However, in the case of sweating into clothing in a cold environment, there seems to be very little lag in power as measured by watts lost; the power adjusts to its new, constant level very quickly, long before the clothing temperature becomes level.

The other physiological feature that we know is important, and that also can be changed by blending, is the amount of water retained in the clothing. This feature is not so important while the work and sweating are going on, for the combined power rate for the combined mechanisms of direct heat loss and evaporation is constant throughout this period; but after the heavy work is over, the amount of water in the clothing will affect the man. With his work level falling back to normal, he himself no longer needs to sweat and be cooled, and yet his clothing continues to "sweat" or to transfer heat (energy) by the combined mechanisms, including evaporation. This can lead to an excessive loss of heat, to chilling, and to lowered endurance after exercise.

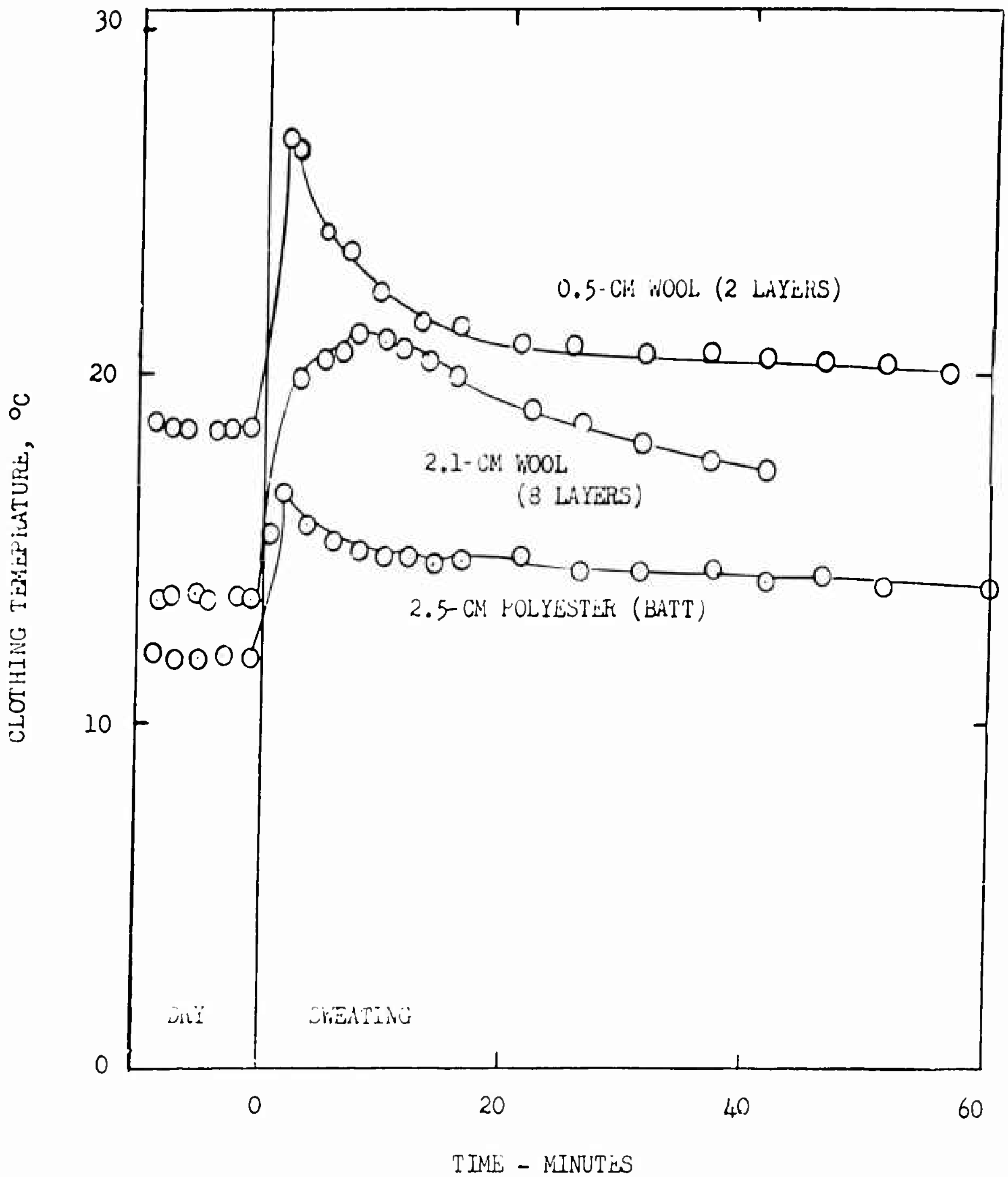

Figure 5. Temperature in three assemblies of clothing, before and after starting sweating in laboratory system with constant skin temperature.

We do not know as much as we should about the optimum fabric structure for reducing water accumulation in clothing, but the evidence points to the value of lofty structure and also to the value of uniform low density, both of which are wool-type fabric characteristics.

4. Review and Forecast of Challenges Involved in Achieving Wool-type Fabrics:

This analysis of wool-type fabrics used for protection against the cold, their relationship to heat and moisture transfer, and the purely structural relations of thickness and hairiness, emphasize the essentially open structure, a characteristic arising from a relative randomness of fiber arrangement. We have seen that relative randomness of structure is a result of certain features of wool-type fibers, such as crimp and varied fiber size and length, and that this randomness can be aided by fabric design and by the fulling process. This is true for all types of fabrics made of wool, but most especially it is true for woolens, where fulling can be emphasized. The changes produced by blending or by fiber substitution tend to be away from a wool-type structure unless special attention is given to retaining the randomness of structure, as by crimp, and to promoting fulling, as by low twist yarns, long floats, and an open texture.

Two challenges arise from this analysis of a wool-type structure. One is to obtain, by some means other than felting, the same high bulk and loftiness of wool in fabrics that are as well suited for hard service as wool is. The various texturizing processes and the application of the differential shrinkage principle are interesting possibilities here, but so far they seem to find more use in sweaters, other knit garments, and luxury articles than in suitings or fabrics for hard service. The other challenge is to obtain structures similar to wool, using low-regain fibers, and to explore the possible effects in clothing of their lower water retention. Results would be of use not only in designing clothing to protect from the cold but, with light clothing, they might lead to provision for better temperature regulation by the body itself in warm environments, thus extending the zone of comfort in clothing in both the cold and warm directions.

5. Acknowledgments:

It is a privilege to note that this report reviews work which has been carried out over a period of years, under the sponsorship of the Quartermaster Corps, through a series of contracts. We are grateful to Dr. S. J. Kennedy, Mr. Louis Weiner, Mr. John Hintermaier, and many others who are now or formerly were members of the Quartermaster research group, for guidance and help. The work here has involved several members of Harris Research Laboratories, particularly Drs. Milton Harris and Norman R. S. Hollies, and Messrs. Arnold Sookne and Herman Bogaty, with the aid of others in doing the experiments. Our debt to workers in other groups is also great, and is at least partly indicated by the references cited.

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Wool-type fabrics have special combinations of features arising from the chemical properties of wool (high water adsorbing capacity and low flammability) and also special mechanical properties of elasticity and long-range stretch that are in part chemical, based on their polymeric structure. The distinctive structural feature of wool in fabric form is a randomness of arrangement of the individual fibers. This randomness is found particularly in woolens, where extensive fiber rearrangement is produced in fulling, but it is also found in worsteds, which have the most regular arrangement of fibers of any wool fabric. However, blending wool with other fibers, especially in worsted fabrics, usually reduces the randomness of fiber arrangement. This may be desirable for summer clothing but it is not desirable for cold weather use. In woolens, wool-type characteristics can be more completely retained by design to promote fulling.

With respect to the relation of clothing to the physiology of heat balance, the relatively greater thickness and lower density of wool-type structures tend to conserve heat and reduce wicking and the accumulation of moisture. However, the high regain of wool tends to increase the accumulation of moisture and to spread the time required for changes due to moisture passage.

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3. Clothing
4. Mechanical properties
5. Military personnel
6. Physiology
7. Synthetic fibers
8. Textiles
I. Fourt, Lyman
II. Monego, Constantin J.
III. Title
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VI. Harris Research Labs.

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Quartermaster Research & Engineering Center, Natick, Mass.
INFLUENCE OF BLENDING ON PROPERTIES OF WOOL-TYPE FABRICS by Lyman Fourt and Constantin J. Monego, 26 pp., illus. (Technical Report TS-116) April 1961

Wool-type fabrics have special combinations of features arising from the chemical properties of wool (high water adsorbing capacity and low flammability) and also special mechanical properties of elasticity and long-range stretch that are in part chemical, based on their polymeric structure. The distinctive structural feature of wool in fabric form is a randomness of arrangement of the individual fibers. This randomness is found particularly in woolens, where extensive fiber rearrangement is produced in fulling, but it is also found in worsteds, which have the most regular arrangement of fibers of any wool fabric. However, blending wool with other fibers, especially in worsted fabrics, usually reduces the randomness of fiber arrangement. This may be desirable for summer clothing but it is not desirable for cold weather use. In woolens, wool-type characteristics can be more completely retained by design to promote fulling.

With respect to the relation of clothing to the physiology of heat balance, the relatively greater thickness and lower density of wool-type structures tend to conserve heat and reduce wicking and the accumulation of moisture. However, the high regain of wool tends to increase the accumulation of moisture and to spread the time required for changes due to moisture passage.

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